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Optimization of Urban Rail Transportation in Emerging Countries Using Operational Research Techniques

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Abstract

Rail systems are gradually becoming the most desirable form of transit infrastructure around the world, partly because they are becoming more environmentally friendly compared with airplanes and automobiles. This paper examines the place of emerging countries in this move of implementing modern rail system that will eventually enhance the realization of a low-carbon society. Network model, transportation model and linear programming algorithms are used to model the present urban rail transport system in Nigeria, as an emerging country, in order to optimize it. Operational research methods, including simplex method and MODI, with the aids of computer software (excel solver and LIP solver) were adopted to solve the resulting models. The results showed that optimization of rail transport system will not only reduce carbon emission but also bring about economic development which is required for the eradication of prevalent poverty in these emerging countries.

Keywords

Rail System, Emerging Countries, Operational Research, Network Model, Transportation Model, Linear Programming Algorithm

1. Introduction

Emerging countries are developing countries which have achieved individual capacity and are on the path to becoming industrialized countries [1]. The list of emerging countries according to the World Bank index (May 2010) [2] includes: Afghanistan, Albania, Algeria, American Samoa, Angola, Argentina, Armenia, Azerbaijan, Bangladesh, Belarus, Belize, Benin, Bhutan, Bolivia, Bosnia and Herzegovina, Botswana, Brazil, Bulgaria, Bur-

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kina Faso, Burundi, Cambodia, Cameroon, Cape Verde, Central African Republic, Chad, Chile, China, Colombia, Comoros, Congo, Dem. Rep., Congo, Rep., Costa Rica, Côte d'Ivoire, Croatia, Cuba, Djibouti, Dominica, Dominican Republic, Ecuador, Egypt, Arab Rep., El Salvador, Eritrea, Ethiopia, Fiji, Gabon, The Gambia, Georgia, Ghana, Grenada, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Honduras, India, Indonesia, Iran, Islam, Rep., Iraq, Jamaica, Jordan, Kazakhstan, Kenya, Kiribati, Korea, Dem. Rep., Kyrgyz Republic, Lao PDR, Latvia, Lebanon, Lesotho, Liberia, Libya, Lithuania, Macedonia, FYR, Madagascar, Malawi, Malaysia, Mali, Marshall Islands, Mauritania, Mauritius, Mayotte, Mexico, Micronesia, Fed. Sts., Moldova, Mongolia, Montenegro, Morocco, Mozambique, Myanmar, Namibia, Nepal, Nicaragua, Niger, Nigeria, Pakistan, Palau, Panama, Papua New Guinea, Paraguay, Peru, Philippines, Poland, Romania, Russian Federation, Rwanda, Samoa, São Tomé and Príncipe, Senegal, Serbia, Seychelles, Sierra Leone, Solomon Islands, Somalia, South Africa, Sri Lanka, St. Kitts and Nevis, St. Lucia, St. Vincent and the Grenadines, Sudan, Suriname, Swaziland, Syrian Arab Rep., Tajikistan, Tanzania, Thailand, Timor-Leste, Togo, Tonga, Tunisia, Turkey, Turkmenistan, Uganda, Ukraine, Uruguay, Uzbekistan, Vanuatu, Venezuela, RB, Vietnam, West Bank and Gaza, Yemen, Rep, Zambia, Zimbabwe, and few other.

A lot of these emerging countries now have urban rail transport projects. This is largely due to the increase in commercial transportation activities brought by development. Nigeria's largest city, Lagos, for instance is constructing a light rail system under a Public Private Partnership (PPP). The first two lines of the urban rail transport project are estimated to cost \$1.4 billion [2]. The development objective of the intermodal and Rail Development Project for Tanzania is to deliver a reliable open access infrastructure on the Dar es Salam-Isaka rail segment. Total project cost include funding from World Bank and non-bank sources in US\$ millions [3]. The developing world is embarking on a massive infrastructure boom, and China wants to build it—and bankroll it—a \$12 billion contract to build a railway stretching to more than 1400 kilometers along the coast of Nigeria. It was China's biggest overseas contract [4]. Kenya Railways Corporation is developing a new standard railway line for passengers and cargo transportation between Mombasa, the largest port in East Africa and Nairobi, the capital city [5]. With a population of 17 million, Cairo is one of the most densely populated cities in Africa. Its railway system operated by Egyptian National Railway (ENR) transports nearly 500 million passengers and 12 million tons of freight each year. Construction of line 3 began in 2007 to accommodate the ever-growing population in Cairo [6]. The Oran tramway project is part of Enterprise du Metro d'Alger's (EMA) plan to build a tram network to improve public transport in Algeria, which was announced in 2006. Light rail development in Algeria is currently targeting the completion of three new systems by 2020. Oran tramway, being one of them [7]. Rail is an effective way to deliver mass transit of large number of people. It provides fast, safe and comfortable transportation from suburbs into city centers or city centers to another city center. The cost of rail projects, both the upfront land acquisition and construction, as well as the ongoing operations and maintenance, is considerable. Thus, governments and institutions must carefully plan, structure and implement rail and road projects to ensure that they deliver value for money, same time and make sure that transport policy objectives are met optimally [8] [9]. Application of operational research technique to urban rail transportation projects in these emerging countries will help to maximize value for money and meeting policy objectives. Linear programming and other transporting models are operational research tools used to optimize the urban rail transportation projects of the developing countries in this paper [10].

Linear programming model is a planning technique that uses mathematical model in maximizing or minimizing appropriate measure to optimize the value of some objective after identifying some constraints [10] [11]. It may be used for solving broad range of problems in different sectors of an economy including health and transportation sectors [11].

The urban rail transit transportation system, in most of the emerging countries, consists of three parts; the carrying tool, infrastructure and operation management [12].

i) carrying tool is a general term of various types of equipment required by the railway and urban transit transport; it consists of safety monitoring, facilities of maintenance and protection.

ii) Infrastructure is the basic device of rail transit transportation, and it mainly consists of public works engineering system, tractive power supply system, and communication signal system. The public works engineering consists of lines, stations and bridges and tunnels.

The tractive power supply system consists of substation, overhead line system and electric power supply. Also the communication signal consists of two parts namely: the communication and signal parts.

iii) Operation management mainly refers to the operation organization and service management system orga-

nizing various transportation resources scientifically and reasonably, and provides high quality transportation services for passengers and owners of cargo based on the requirements on the transport of travellers and goods. This involves mainly: The passenger flow demand forecasting, demand rules analysis, Passenger transport path, transportation organization model, train operation plan, train graph, motor train unit application, train and station organization. The major constraints of rail transport market in sub-Saharan Africa are as follows:

- 1) The railway network is limited.
- 2) The technical condition of railway infrastructure is very poor. This has manifested in form of
 - (a). Aging tracks-insufficient, rail wear, deteriorating earthworks.
 - (b). Poor conditions of most structures.
 - (c). Lack of technical expertise and poorly motivated workforce.
 - (d). Obsolete signals and telecommunication, and lack of spare parts
 - (e). Lack of investment in the sector and corruption.
- 3) (i). Africa operates a very limited volume of traffic compared with the rest of the world: With a length of around 54,000 km, the network of rail of Africa represents only 5 percent of the worldwide network [13]. Railway has a competitive advantage to other mode of transportation on large volumes of traffic. Sub-Saharan Africa operates less than 1 percent of the world volume of freight and passenger rail traffic [13].
- 3 (ii). The inter-country trade in sub-Saharan Africa is very limited: The percentage of inter-African export exchanges is still low as most Sub-Saharan African countries are still economically dependent on overseas markets, both for export and import. The railway pattern is still mainly oriented on exporting the resources to other continents, and less on regional trade [13].

2. Formulation of Problem

In order to solve the associated problems of urban rail transportation, especially in the emerging countries, we optimize the three parts that makes up the urban rail transportation system, namely; carrying tool, infrastructure and operation management. These three parts constitutes our decision variables as follows:

2.1. Decision Variables

Let

- x_1 represent the carrying tool
- x_2 represent the infrastructure
- x_3 represent the Operation management

2.1.1. Carrying Tool (x_1)

Let

- x_{11} = safety monitoring
- x_{12} = facilities of maintenance and protection

2.1.2. Infrastructure (x_2)

Let

- x_{21} = Public works engineering system
- x_{22} = tractive power supply system
- x_{23} = communication signal system

2.1.3. Operation Management (x_3)

Let x_{31} = Passenger flow demand forecasting

- x_{32} = demand rules analysis
- x_{33} = Passenger transport path
- x_{34} = transportation organization model
- x_{35} = train operation plan
- x_{36} = train graph
- x_{37} = motor train unit application
- x_{38} = train and station organization

2.2. Contributions

From the data gathered, the percentage of success (contribution) of each of the decision variables are given in **Table 1** [12] [13].

Therefore, the contributions c_{1j} as regards the carrying tool are as follows:

$$c_{11} = 10, \quad c_{12} = 15$$

The contributions c_{2j} as regards the infrastructure are as follows:

$$c_{21} = 5, \quad c_{22} = 10, \quad c_{23} = 5$$

The contributions c_{3i} as regards the operation management are as follows:

$$c_{31} = 6, \quad c_{32} = 5, \quad c_{33} = 5, \quad c_{34} = 10, \quad c_{35} = 10, \quad c_{36} = 4, \quad c_{37} = 7, \quad c_{38} = 8$$

The performances of the decision variables towards optimization of urban rail transportation in emerging countries, therefore, are respectively:

$$\sum_{j=1}^2 \sum_{i=1}^2 c_{1j} x_{1i} = c_{11} x_{11} + c_{12} x_{12} \quad (1)$$

$$\sum_{j=1}^3 \sum_{i=1}^3 c_{2j} x_{2i} = c_{21} x_{21} + c_{22} x_{22} + c_{23} x_{23} \quad (2)$$

$$\sum_{j=1}^8 \sum_{i=1}^8 c_{3j} x_{3i} = c_{31} x_{31} + c_{32} x_{32} + c_{33} x_{33} + c_{34} x_{34} + c_{35} x_{35} + c_{36} x_{36} + c_{37} x_{37} + c_{38} x_{38} \quad (3)$$

2.3. Objective

The objective is to maximize total performances of the decision variables. That is:

Maximize

$$Z = \sum_{j=1}^2 \sum_{i=1}^2 c_{1j} x_{1i} + \sum_{j=1}^3 \sum_{i=1}^3 c_{2j} x_{2i} + \sum_{j=1}^8 \sum_{i=1}^8 c_{3j} x_{3i} \quad (4)$$

$$= c_{11} x_{11} + c_{12} x_{12} + c_{21} x_{21} + c_{22} x_{22} + c_{23} x_{23} + c_{31} x_{31} + c_{32} x_{32} + c_{33} x_{33} \\ + c_{34} x_{34} + c_{35} x_{35} + c_{36} x_{36} + c_{37} x_{37} + c_{38} x_{38} \quad (5)$$

2.4. Resource Utilization

Let a_{ij} be the amount of resource j used to achieve one unit of decision variable x_i . From the data gathered and with some simulations, we have the following:

Table 1. Decision variables and their corresponding contribution.

Decision variable	Sub Decision variable	Description	Percentage (weight) of success/ contribution
X_1	X_{11}	safety monitoring	10
	X_{12}	facilities of maintenance and protection	15
X_2	X_{21}	Public works engineering system	5
	X_{22}	tractive power supply system	10
	X_{23}	communication signal system	5
X_3	X_{31}	Passenger flow demand forecasting	6
	X_{32}	Demand rules analysis	5
	X_{33}	Passenger transport path	5
	X_{34}	Transportation organization model	10
	X_{35}	Train operation plan	10
	X_{36}	Train graph	4
	X_{37}	Motor train unit application	7
	X_{38}	Train and station organization	8

- a_{11} = unit cost of achieving safety monitoring
 a_{12} = unit cost for acquiring facility of maintenance and production
 a_{22} = unit cost for tractive power supply system
 a_{23} = unit cost of installing communication signal system
 a_{31} = unit cost to achieve passenger flow demand forecast
 a_{32} = unit cost to carry out demand rules analysis
 a_{33} = unit cost to achieve the transport path
 a_{34} = unit cost of formulating transport organization model
 a_{35} = unit cost of building train operations plan
 a_{36} = unit cost of making train graph available
 a_{37} = unit cost of motor train unit application
 a_{38} = unit cost of proper train and station organization

The amount of available resources used to achieve a unit of the decision variables are represented in **Table 2** as follows [12] [13].

2.5. Constraints

$$a_{11}x_{11} + a_{12}x_{12} \leq 25\% \text{ of } T$$

$$a_{21}x_{21} + a_{22}x_{22} + a_{23}x_{23} \leq 20\% \text{ of } T$$

$$a_{31}x_{31} + a_{32}x_{32} + a_{33}x_{33} + a_{34}x_{34} + a_{35}x_{35} + a_{36}x_{36} + a_{37}x_{37} + a_{38}x_{38} \leq 55\% \text{ of } T$$

$$a_{11}x_{11} + a_{12}x_{12} + a_{21}x_{21} + a_{22}x_{22} + a_{23}x_{23} + a_{31}x_{31} + a_{32}x_{32} + a_{33}x_{33} + a_{34}x_{34} + a_{35}x_{35} + a_{36}x_{36} + a_{37}x_{37} + a_{38}x_{38} \leq T$$

$$a_{ij} \geq 0; i = 1, 2, 3, ; j = 1, 2, \dots, 8$$

where T is the total amount available for rail transport in sub-Saharan African countries, which is put at \$20 million. in a year, on the average, for the purpose of this paper.

2.6. The Model

Maximize

$$\begin{aligned}
 Z = & 10x_{11} + 15x_{12} + 5x_{21} + 10x_{22} + 5x_{23} + 6x_{31} + 5x_{32} + 5x_{33} \\
 & + 10x_{34} + 10x_{35} + 4x_{36} + 7x_{37} + 8x_{38}
 \end{aligned}$$

Table 2. Values of resources used to produce a unit of different decision variables.

Resources	Values
a_{11}	25
a_{12}	50
a_{22}	25
a_{23}	25
a_{31}	5
a_{32}	5
a_{33}	5
a_{34}	5
a_{35}	10
a_{36}	5
a_{37}	7.5
a_{38}	12.5

Subject to

$$25x_{11} + 50x_{12} \leq \$5 \text{ million}$$

$$25x_{21} + 25x_{22} + 25x_{23} \leq \$4 \text{ million}$$

$$5x_{31} + 5x_{32} + 5x_{33} + 5x_{34} + 10x_{35} + 5x_{36} + 7.5x_{37} + 12.5x_{38} \leq \$11 \text{ million}$$

$$25x_{11} + 50x_{12} + 25x_{21} + 25x_{22} + 25x_{23} + 5x_{31} + 5x_{32} + 5x_{33} + 5x_{34} + 10x_{35} + 5x_{36} + 7.5x_{37} + 12.5x_{38} \leq \$20 \text{ million}$$

$$x_{ij} \geq 0; i = 1, 2, 3; j = 1, 2, \dots, 8$$

3. Model Solution

The model is first of all written in its standard form before applying simplex method to solve it.

3.1. Standardized Model

Maximize

$$Z = 10x_{11} + 15x_{12} + 5x_{21} + 10x_{22} + 5x_{23} + 6x_{31} + 5x_{32} + 5x_{33} + 10x_{34} + 10x_{35} + 4x_{36} + 7x_{37} + 8x_{38}$$

Subject to:

$$25x_{11} + 50x_{12} + s_1 \leq 5,000,000$$

$$25x_{21} + 25x_{22} + 25x_{23} + s_2 \leq 4,000,000$$

$$5x_{31} + 5x_{32} + 5x_{33} + 5x_{34} + 10x_{35} + 5x_{36} + 7.5x_{37} + 12.5x_{38} + s_3 \leq 11,000,000$$

$$25x_{11} + 50x_{12} + 25x_{21} + 25x_{22} + 25x_{23} + 5x_{31} + 5x_{32} + 5x_{33} + 5x_{34} + 10x_{35} + 5x_{36} + 7.5x_{37} + 12.5x_{38} + s_4 \leq 20,000,000$$

$$x_{ij} \geq 0; i = 1, 2, 3; j = 1, 2, \dots, 8$$

3.2. Simplex Method of Solution

In this research work, we used the simplex method algorithm to solve the standardized linear programming model. The initial tableau was formed from the standardized linear programming model, after which linear programming solver (LIPS) software was adopted to arrive at the following results, with optimum solution equals 25,600,000.

Table 3 shows the values of the different decision variables using LIPS [14].

4. Results Discussion

The Results obtained in table show that three of the decision variables are very significant, namely: x_{11} , x_{22} and x_{34} . That is, Safety monitoring, Tractive Power Supply, and Transportation organization model. In any of the emerging countries, these three factors, classified under carrying tools, Infrastructure and operational management respectfully, are very critical in optimizing the urban rail transport in emerging countries. The result revealed that if 200,000 USD is set aside to take care of the safety monitoring, 160,000 USD is set aside for tractive power supply, and 2,200,000 USD is set aside to take care of transportation organization model for urban rail transportation, then the optimum value of the objective, in terms of USD is 25,600,000. Substituting the values of x_{11} , x_{22} and x_{34} into the objective function gives us the optimum value. This value is greater than the average amount available for investment in Rail transportation, which was put at 20,000,000 USD on the average, by 5,600,000 USD. This is an advantage. It is important to note that x_{34} representing transportation organization model, has the highest value, which suggests its importance among the decision variables. Finally, the factors capable of hindering the achievement of the optimization of rail transportation in the emerging countries, such as corruption and unnecessary bottle necks should be discouraged.

Table 3. Optimal feasible values of the decision variables.

Variables	Represented by	Value
X_{11}	X_1	200,000
X_{12}	X_2	0
X_{21}	X_3	0
X_{22}	X_4	160,000
X_{23}	X_5	0
X_{31}	X_6	0
X_{32}	X_7	0
X_{33}	X_8	0
X_{34}	X_9	2,200,000
X_{35}	X_{10}	0
X_{36}	X_{11}	0
X_{37}	X_{12}	0
X_{38}	X_{13}	0
S_1	X_{14}	0
S_2	X_{15}	0
S_3	X_{16}	0
S_4	X_{17}	0

5. Conclusion

In this research paper, optimization of urban rail transportation was considered. The problem was modeled as a linear programming problem, which was solved using simplex method with the aid of computer software—Linear programming solver (LIPS). It is shown that all the three categories of factors leading to optimization of urban rail transportation in emerging countries are important in the process of maximization. Specifically, a good transportation organization model must be built in order to attain optimality of urban rail transportation in these countries.

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